

COMPRESSED GAS LIQUID™ CARRIERS (CGLC): NEW CONCEPT FOR TRANSPORTING STRANDED AND REMOTE GAS

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SUMMARY

An explorer having mid to small size gas reserves (8TCF and less) that are located in remote locations must have access to a pipeline transportation system. If not, their gas is stranded. To be able to drill up and bring on the production the explorer must realize an acceptable wellhead netback (or how much he gets) for his gas. The producer must also be able bring on his gas production with the least capital expense. With rising field development costs, the explorer faces serious challenges to get his field developed in a timely manner and within budget.

In receiving the gas, the market also faces significant challenges, that of rising receiving terminal costs, environmental issues and a flexible and reliable source or sources of gas supply having the lowest transportation cost possible. SeaOne Maritime Corp. has developed a marine gas transportation system (CGLC) that not only provides the needed wellhead netback but also allows the explorer to produce and deliver the full value of his gas production to market.

NOMENCLATURE

ABS	American Bureau of Shipping
BCF	Billion Standard Cubic Foot (ft ³)
BTU	British Thermal Unit
CAPEX	Capital Expense
CGL™	Compressed Gas Liquid™
CGLC	Compressed Gas Liquid™ Carrier
CNG	Compressed Natural Gas
LNG	Liquid Natural Gas
LPG	Liquefied Petroleum Gas
LR	Lloyds Register of Shipping
MMSCF	Million Standard Cubic Foot (ft ³)
NGL	Natural Gas Liquids
OPEX	Operating Expense
STP	Standard Temperature & Pressure
TCF	Trillion Standard Cubic Foot (ft ³)
ULCC	Ultra Large Crude Carrier
VLCC	Very Large Crude Carrier

1. INTRODUCTION

1.1 BACKGROUND

Natural gas represents a source of clean energy for which global demand is increasing. Over three-quarters of the world's known offshore reserves of natural gas remain undeveloped due to the high cost of transportation. These reserves are found in far off and remote locations as gas pools or gas associated with to oil production. The size of these pools is often substantial (typically 8.0 TCF and below), yet they remain below the critical size required for the economics demanded for new long-term maritime LNG development.

LNG requires large capital needs and considerable process energy to achieve feasibility. Upstream capital costs are in the billions of dollars (US\$) to establish the LNG liquefaction facilities. Additional capital expense is required at the market end to set up receiving terminals for re-gasification. There are separate and *additional* capital costs required to produce and deliver the LPG's to market. Long lead times and considerable community opposition (also known as the NIMBY, or 'Not-In-My-Back-Yard') to receiving terminal locations or expansion in market areas have only served to focus industry on the returns of the largest of these gas fields.

Overall, a LNG ship carries natural gas product under storage conditions at a volumetric ratio of approximately 600 times that of the product at STP conditions. This is achieved with storage conditions of -260°F (-162°C) and atmospheric pressure. Large ships of this type carry approximately 3.0 BCF and more of natural gas.

Specific distillates of natural gas, Butane and Propane, both also produced from crude oil refining, are gaseous at ambient temperature and pressure and yet are liquid when stored and transported under modest pressure or in a moderate refrigerated state (hence the name LPG). Specialised LPG ships have been developed to utilise these particular properties, being either pressurised, fully-refrigerated, or semi-refrigerated (trade as both pressure and refrigerated storages) containment systems.

Compressed Natural Gas (CNG) has also been developed as a shipping concept, relying on the high pressure containment technology used in conventional pressure vessel CNG storage and in pipeline systems to provide a form of concentrated gas storage which can be fitted onboard ships. The CNG concept that has been around for a long time, seeks to offer savings by removing the need for the expensive onshore refrigeration trains required for LNG. However, CNG still needs separate gas conditioning and process systems to get the production gas segregated and suitable for transportation. A separate LPG processing and transportation system is also needed.

However, alternative gas transportation technologies exist which avoid the extremely low temperatures and expensive onshore liquefaction trains, or the high pressure containment systems, and offer more modest containment requirements better suited to raw production gas handling, sea transportation and pipeline quality gas delivery to market.

1.2 EMERGING GAS TECHNOLOGIES

Although gas demand is growing, a simple development approach, with appropriately lower CAPEX and OPEX, is required to serve the smaller or “stranded” reserves. Hence, there has been a re-emergence of CNG proposals. Processing is still required to condition the natural gas for shipment as CNG. Condensates, NGL's and water are removed from the product before it is able to be compressed for storage in marine transportation containers. Like LNG, the LPG's are processed and shipped separately.

Proponents of CNG have tested various combinations of pressure and temperature in an attempt to achieve optimal volumetric efficiency compared to containment system mass and cost. It is reported that CNG technology offers refrigerated compressed storage systems typically operating at 1800 psig at -20°F (-29°C), or pressure only systems operating at 3000 to 3600 psig at atmospheric temperatures in order to achieve compressed volumetric storage ratios in the order of 250 to 300 times the natural gas density at STP. Yet, CNG systems have not yet entered full commercial development. Equipment development and economic costs are some of the major hurdles being addressed by various groups attempting to develop this technology, over the past 10 years.

The practicality of the proposed patented process solutions and offloading the CNG product from storage, at the required volumetric ratio levels previously mentioned, are proving to be energy intensive and time consuming to realize. The energy value of the production gas is not realized at market. Commercial implementation of this technology has been slow to emerge as there are no compelling economics. In general, the largest vessel designs proposed will deliver 0.7 to 1.0 BCF of CNG product. Published figures concerning their economic realm of operation appear to place CNG ships in costal or regional, as opposed to mid or trans-ocean service.

2. FILLING THE VOID

2.1 COMPRESSED GAS LIQUID™

Even with the re-emerging CNG technology, there still remains a need for an economically viable, efficient and flexible trans-ocean transportation system for moving natural gas from the remote or stranded fields to market. Also, any marine gas transportation system must provide both the producer and the market value. The emergence of SeaOne's CGL™ Carrier or CGLC using Compressed Gas Liquid™ (CGL™) technology is designed to fill this void.

CGL™ transport gains its advantages from proven gas property research work. This work has confirmed that under exact conditions of pressure, temperature along with specific mixture compositions, a more dense volumetric packing of the natural gas can be attained within a given volume than can be achieved in the same space using natural gas alone under the same conditions.

The concept of carrying more gas within a liquid matrix of NGL's has given rise to the term 'Compressed Gas Liquid™' for this method of transport. The term 'LNG Lite™' has also been used to describe its relatively higher volumetric storage ratio (compared to CNG) using less exotic equipment and at substantially lower CAPEX and OPEX than that required for LNG systems.

With its pipeline roots, the CGL™ concept deploys a continuous large diameter steel pipeline packed within the cargo holds of a converted vessel or above deck on a new-build vessel for transporting the production gas as a liquefied cargo.

In an integral carrier transportation model [Figure 1], the CGL™ Carrier is entirely self-contained. It carries CGL™ processing equipment on one side of the ship to load the raw production or conditioned natural gas and create the storage liquid for containment within the pipeline cargo system. On the other side of the carrier, an offloading process train is provided to separate the natural gas from its NGL 'solvent'. The natural gas is offloaded and the NGL returned to storage within the pipeline system ready to load the next shipment.



Figure 1: Integral CGL Carrier

In a shuttle carrier transportation model, a loading barge is placed at the production gas source, where the raw production gas is loaded directly from the field onto the barge. The loading barge [Figure 2] has all the necessary raw gas conditioning and CGL™ processing equipment to load the entire conditioned produced natural gas in a liquid form onto the CGLC and into the refrigerated pipeline cargo system. At the market end, the CGLC unloads the liquefied gas cargo onto an offloading barge [Figure 3] that segregates the NGL's into their individual components allowing for refined products to the required specification into a receiving pipeline or storage system.

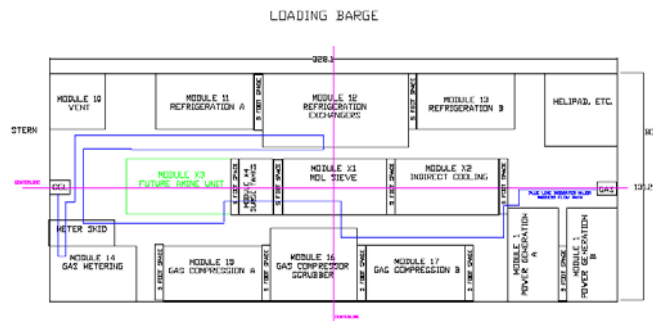


Figure 2: Loading Barge - Equipment Plan View

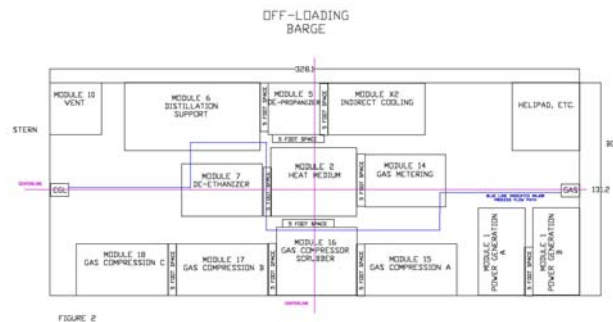


Figure 3: Offloading Barge - Equipment Plan View

The SeaOne business models, 'integral' or 'shuttle' configurations, for the marine transportation of production or conditioned natural gas provides for better CAPEX and OPEX while also providing value to the explorer and market.

This transportation method for production or conditioned natural gas requires minimal infrastructure, only an offshore buoy at each end of its voyage to load from and offload too. These buoys are connected by conventional undersea pipelines to production and market facilities, no other facilities are required. The shore bound fixed high capital infrastructures of LNG and CNG technologies are taken out of the equation. The resulting system reduces capital expenditures and lead times to put a project into service. Simplicity and scalability provide fast in-service simple capacity.

2.2 SCOPE OF TECHNOLOGY

Designs of CGL™ Carriers include conversions of single-hull Suezmax crude oil tankers which when converted can deliver up to 1.5 BCF of liquefied natural gas cargos, and new-build designs that are available for delivery of 0.5 BCF through to 3.0 BCF (CGLC designs are available for up to 6.0BCF) of sales gas cargo to market.

The containment system, which is a liquid filled pipeline system and has been Approved in Principle by both ABS and Lloyds, can be constructed to pipeline design codes. These codes permit thinner wall thickness for *liquid* service compared to *gas* service under the same conditions. Through more work in the area of limit state design, possibilities exist for further reductions in wall thickness, and improvements in metallurgy consistent with safety requirements.

In order to meet a twenty-four (24) month project timeline for on-service, SeaOne has retained the American Bureau of Shipping (ABS) to provide Classification Services for its CGLC's. SeaOne is currently under General Approval Rules for Classification of SeaOne's CGL™ carrier's.

The present containment system designs yield a net volumetric ratio of 306 times that of the natural gas product at standard conditions. Consistent with the thinner wall reduction for liquid transport, when compared to current CNG proposals, SeaOne's CGL™ system offers a 2:1 benefit in the mass ratio of gas stored to containment steel weight, measured on a lb/lb basis [Figure 4].

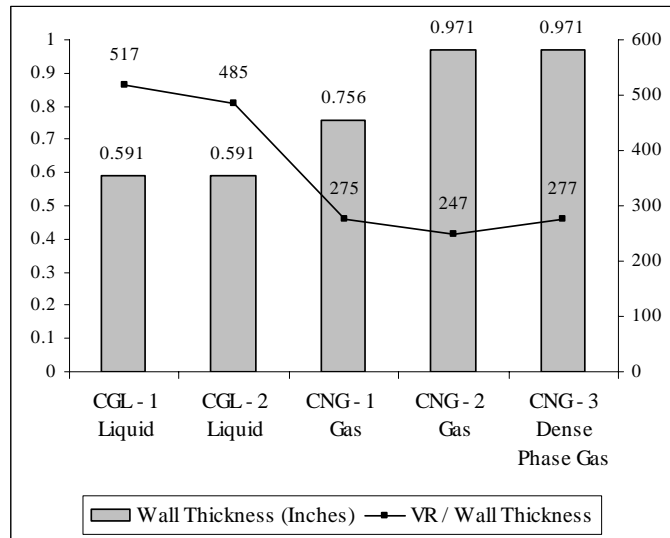


Figure 4: Wall Thickness vs Storage Volumetric Ratio

Besides existing vessel conversions, SeaOne's CGL™ Carrier designs cater to new-build ships of small and higher capacity, and both are available in either an 'integral' or 'shuttle' CGL™ Carrier design. The shuttle carrier configurations allow for multiple CGL™ Carriers that make use of separate barges or other type of floating vessels for loading and offloading of the gas. For the shuttle carrier the process modules are mounted on these service barges or vessels instead of being integral to the CGL™ ship.

3. COMPRESSED GAS LIQUID CARRIER DESIGN

From the outline description of the CGL™ technology, given in the section above, it is obvious that this type of containment system is suitable for marine transportation use. Neither the transportation refrigeration temperature nor pressure present any particular concerns for a ship based transportation platform, indeed both containment requirements having been exceeded in other ship designs, as well as being within the scope of the IGC Code [1] and other International regulations. The CGL™ process equipment has been designed on a skid based modular format from the outset, to a convenient size and weight, such that location of the process equipment modules on the ship is flexible within the general 'flow' of the processed cargo, suiting a fragmented deck arrangement or a single open deck area, with some equipment/modules capable of over-stacking.

It was therefore necessary but also practical to develop a tailored marine transportation platform which could perform to the commercial requirements of the project. To this end, both ship conversion and new-build options were considered. Several outline CGL™ tanker designs have been developed, ranging from Aframax to ULCC sized crude oil tanker conversions, and a range of optimised new-building designs intended for up to 6.0 BCF gas volumes. However, common to all the ship designs is the basic cargo hold design and weight distribution required to accommodate the CGL™ containment system. It should be noted that the ship conversion option has considered many ship types and identified a number of suitable platforms, but tankers were identified as the most likely commercial option for conversion, particularly a 'phase-out' single hull tanker. Each of the vessel designs developed to date has been optimised around particular commercial gas volumes.

3.1 BASIC NAVAL ARCHITECTURE

The fundamental requirement for any ship design is that the weight and displacement are in balance, and that the available ship volume can accommodate the cargo volume and all other spaces required for the operation of the ship. For a CGL™ tanker, the cargo and its containment system represent the largest demands for weight and volume, although deck area and service volumes must be retained for the cargo process plant on an 'Integral' CGL™ Carrier.

Due to the extensive development and engineering work completed by SeaOne on the containment and process systems, the volume and weight requirements for certain capacities of CGL™ Carrier were clearly defined. A typical high block coefficient vessel, such as an oil tanker, has no problem in providing the displacement necessary for this type of gas carrier, although service speed would be limited to the norm for this hull type, whereas typical faster commercial hull forms need more consideration of displacement compared to cargo capacity.

For a CGL™ ship, the cargo is 'light' in comparison to the constant weight of the heavy cargo containment system and the hull, i.e. the loaded and unloaded conditions of the ship do not vary greatly. Thus, the need to compensate for a lack of cargo when empty is much reduced. In a CGL™ Carrier, ballast will principally be required for stability and maintaining trim depending on cargo intake and/or consumption of consumables, with little ballast pumped during loading/off-loading operations which saves on time and ballast system cost/complexity (and later in life – maintenance).

In order to maximise cargo capacity within the available space the CGL™ pipe containment system projects above the main deck of the ship, near to the vertical centre of gravity limit for the stability of the hull form under consideration. Although the weight of the containment system is evenly distributed along the cargo region, the effect on longitudinal strength of the ship by penetrating the upper deck requires careful consideration. However, in essence this issue is no different to the Bulk Carrier and Container Ship structural configurations, and solutions readily exist to compensate for the Main Deck openings. It is normal practice for the CGL™ Carrier structural arrangements to be proved by Finite Element modelling.

The watertight integrity of the ship must also be considered, as well as the need to keep the cargo holds refrigerated to -40°C and insulated from the surrounding steel structure. At this temperature, and even for the lower 'design temperature', the insulation scheme required over the faces of the cargo holds is not excessively thick, and nor is it complicated by the hold structure as the cargo hold faces are all kept flush with all stiffeners arranged in the surrounding spaces. This allows more common temperature tolerant steel grades to be used throughout the hull (indeed normal shipbuilding Class approved steel grades), except for the CGL™ containment pipe supports within the cargo hold region where a very low temperature steel grade is required.

It should be noted that the modular nature of the CGL™ pipes, and their ability to be removed, has resulted in an integral support system requiring minimal structural intrusion from the ship's hold sides or tank top. During the design phase, ship motion study results were used to feed dynamic acceleration values into both the integral support system and the hold support points.

The ability to remove the CGL™ pipes also assists with through life maintenance issues (although the installation is designed for the life of the vessel), and provides the possibility of installing the containment system at a site remote from the hull fabrication shipyard. Indeed the ship conversion and process/pipe installation facilities can be extremely remote from each other as the basic ship is designed to be navigable without the containment system onboard through use of temporary over ballasting. The need to provide access for CGL™ pipe removal has led to the development of a dedicated hatch cover arrangement on top of the cargo hold deck houses which incorporate a gantry type handling crane for the covers and containment pipes (vertical pipe configuration).

The depth of the double bottom spaces in way of the cargo holds were based on current MARPOL [2] double hull tanker practice for theoretical damage penetration, and the depth of structure needed to support the hold weights with minimal deflection across the span of the cargo hold. The need to provide sufficient buoyancy to restrict the vessel's draught (for commercial or hull scantling reasons) means that CGL™ ships need more side tank volume than a double hull oil tanker.

Some of the proposed CGL™ ship designs feature an accommodation located forward, although the machinery is conventionally located aft. While this may offer some benefits, principally clear vision forward of the cargo hold deck houses, it almost certainly results in a vessel which is larger than would otherwise be required, because (as with conventional oil and gas carriers) it is not permitted to locate the cargo beneath the accommodation. This part of the hull is therefore unavailable for cargo storage, and it is as well to make use of it as a machinery space. However, even in this case it is possible to generate designs which can use more than 70% of the ship length for cargo purposes.

3.2 VESSEL CONVERSION

Conversion to a CGL™ Carrier typically involves the installation of the modular pipe containment system into the central tanks of a vessel, with the process modules to be fitted on the Main Deck side areas. Although a number of vessel types were considered for conversion, the availability of numerous (and possibly sister vessel) single skin oil tankers, due to the MARPOL phase-out, and the suitability of their centre cargo tanks to accept a double bottom and form a structurally clean CGL™ cargo hold, made them the natural commercial choice for first consideration. Also for this vessel type, only minimal modifications would be required on the existing non-cargo related ship systems, except for removal the oil cargo pipework.

For the purposes of this paper a Suezmax oil tanker study vessel will be used to demonstrate the suitability of the proposed vessel type for conversion to a CGL™ Carrier of about 1.5 BCF (70,000 m³) sales gas capacity. Other standard oil tanker sizes ranging from Aframax to ULCC have also been studied for their suitability to carry CGL™ of differing capacities.

Whilst a modular gas storage method is best suited to cargo containment operations it does have disadvantages when integrating with an existing ship structure, particularly a vessel designed for the carriage of fluids. However through suitable structural modifications these problems may be overcome. The typical structure of a tanker will include items such as web frames, deck head structures and bulkhead supports which need to be modified to open out the centre tanks for the modular containment pipes. An additional double bottom structure has also to be included to provide support for the pipes. The double bottom depth is typically in compliance with the damage requirements of the IGC Code [1].

In order to fit the required capacity of CGL™ pipes within the vessel, it was necessary to remove the Main Deck structure in way of the centre tanks, which caused a reduction in the section modulus of the vessel and therefore impacted on longitudinal strength. In addition, to maximise the hold floor area it was necessary to remove the section of each web frame within the centre tank, this includes the typical radius brackets at the bottom, and the deckhead section of the frames. The lost modulus of these items will be largely replaced by the new double bottom type structure including supporting floors, the inclusion of additional full width stringers in the wing tank spaces toward the Main Deck level, and the addition of heavy continuous coamings around the central deck openings [Figure 5].

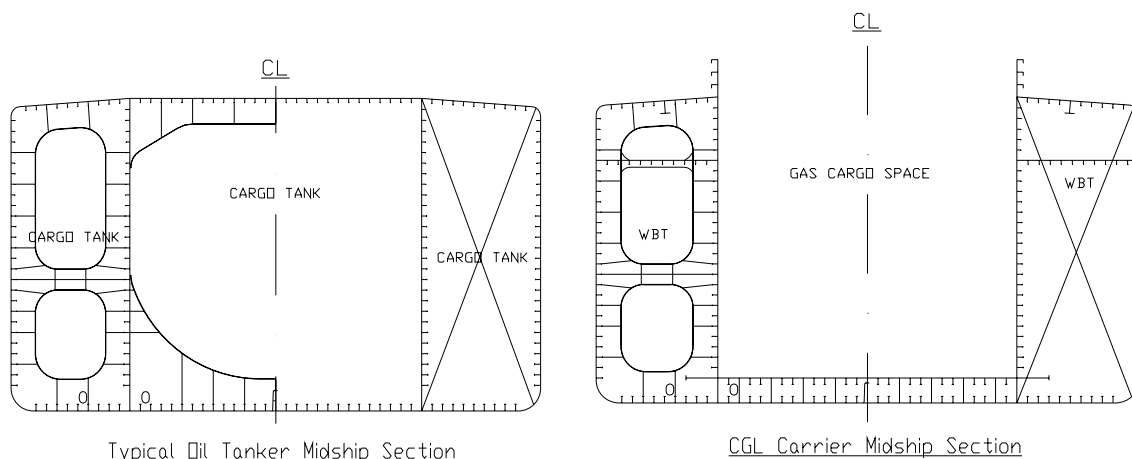


Figure 5: Typical Converted Tanker Midship Section

In addition to these modifications, it would be necessary to double skin the existing transverse oil-tight bulkheads with several stringers at varying heights to form a cofferdam space between the cargo holds. This provides additional resistance to the torsion loading on the cargo region, as well as providing clean and easily insulated hold ends with all stiffening contained within the cofferdam space. The intention being to keep the existing normal grade steel bulkhead structure away from the refrigerated cargo space without extensive renewals.

Assessment of the revised Midship Section indicated that the magnitude of section modulus had been reinstated to a greater level than the original, however there was now a much greater difference between the deck and keel values, indicating that the keel was proportionally 'stiffer' than the deck, due to the neutral axis lowering slightly. The implications for this were checked in detail by undertaking a Finite Element Analysis on the cargo region, and the results indicated both that the deck coaming stresses were within limits, and that the overall scheme of structural changes were satisfactory. The steel weight estimate for a Suezmax sized oil tanker conversion indicate that approximately 1100 metric tonnes will be removed from the Main Deck and centre cargo tanks, and that approximately 4000 metric tonnes will have to be installed to the surrounding longitudinal structure and bulkheads.

The height of the CGL™ containment pipes extends significantly above the Main Deck and impacts on the typical oil tanker Wheelhouse visibility requirements, as defined in SOLAS [3]. Whilst higher pipe stacks can be placed in the holds towards the aft of the vessel with the forward holds to a lower level, it was concluded that to standardise the containment pipe modules and maximise the cargo capacity, it would be preferable to raise the Wheelhouse where possible. Typically on a Suezmax oil tanker the wheelhouse would have to be raised by a maximum of two accommodation deck levels in order to comply where the maximum CGL™ cargo volume is desired. The forward accommodation was not pursued in the ship conversion option due to the limited area available for such a modification in association with the other fore deck alterations required to accommodate the Bow Loading System.

A detailed investigation of the intact and damage stability characteristics was undertaken on the new vessel configuration with constant CGL™ containment pipe and process module weights included. The intact stability was found to comply with the IMO requirements of Resolution A.749 for the cargo capacity required. However, the stability would diminish rapidly as the CGL™ pipe heights were increased above the Main Deck, and ballast weight was lost against the vessel's maximum displacement, and hence an optimum cargo capacity was quickly identified. The damage stability characteristics were calculated and checked against requirements of the IGC Code [1]. 'Two compartment' damage was applied along the length of the vessel, based on the required damage extents, and all damage case parameters were found to be compliant with the prescribed criteria, including longitudinal strength.

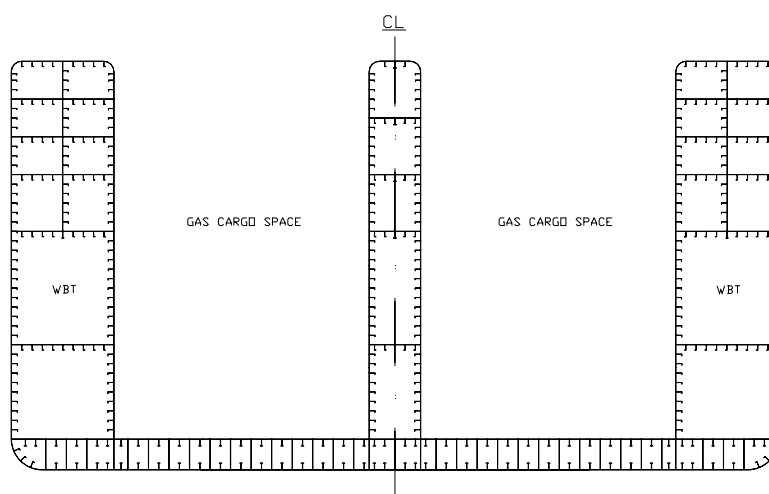
A sea-keeping study looked at the accelerations experienced by the CGL™ containment pipes, as well as the behaviour of the vessel. The scenarios calculated considered changes in vessel speed, wave heading direction, and sea state conditions, with the cargo accelerations being fed into the SeaOne pipe design calculations. The ship behaviour in terms of probability of propeller emergence, slamming and 'green seas' was found to be very similar to that of the donor oil tanker.

3.3 NEW-BUILD VESSEL

The new build option of a 'clean sheet' CGL™ Carrier design involves accommodating the same modular pipe containment system and deck mounted process modules, but allowing optimisation of the design in terms of cargo volume, process integration with ship systems (reducing the module numbers and deck area required), and vessel performance characteristics (speed to market being one of the key commercial drivers in the development of stranded/remote gas). The divergence with the ship conversion option is that the cargo hold dimensions and configuration can be fully optimised for maximum CGL™ capacity, and hull forms can be tailored to the speed requirements of the market.

The new-build CGL™ Carrier designs which were developed were required to cover a range of capacities from 0.5 BCF to 6.0 BCF. The associated process modules were again to be mostly installed on the Main Deck, although the common systems between the process plant and vessel were expected to be integrated within the ship's machinery space(s). The prime movers for generating the ship propulsion power, for cargo loading / unloading, and for other hotel and process services, were also to be provided from below the Main Deck in conventional machinery spaces. It should be noted that although no specific ship service requirements were imposed on the new-build designs, i.e. maximum width requirements, draft requirements, or minimum turning requirements, the construction capability and repair ability of shipyards was taken into account during the studies, particularly for the larger capacity vessels. One service requirement which was identified was a service speed in the region of 20 to 23 knots.

The starting point for any new-build design was the need to provide adequate cargo hold volume and tank top deck space to accommodate the requisite number of CGL™ storage pipes. As per the oil-tanker conversion discussed above, a 'clean' sided cargo hold was desirable with double skin transverse bulkheads between each hold, and ballast spaces provided to port, starboard and in a central double bottom. This arrangement keeps all stiffeners external to the refrigerated and insulated cargo hold, and hence available for inspection without the need to vent and heat the containment system. The larger capacity new-build designs will have the cargo holds separated by a central longitudinal cofferdam space [Figure 4]. This arrangement was influenced by the need for adequate structure to satisfy the longitudinal strength requirement of the larger cargo volume ships.



Typical Newbuild CGL Carrier Midship Section

Figure 6: Typical New-build Tanker Midship Section

With regard to accommodating the deck mounted process modules, the new-build ship designs were developed as either an 'Integral' or 'Shuttle' CGL™ Carrier. The integral carrier being generally smaller in cargo capacity with a full complement of loading and offloading process modules onboard. Whereas the shuttle carrier designs generally extend to the 6.0 BCF capacity but with only those process modules required for maintaining containment onboard, with the loading/offloading process equipment being located on separate 'floating production' type barges at the respective buoys. Depending on which type of CGL™ Carrier was being considered, an adequate area of Main Deck would have to be allowed for at an early stage.

In order to maximise the cargo capacity within the minimum new-build hull dimensions derived from the required cargo hold volume and deck area, it was again necessary to stack the CGL™ pipe modules to a height above the ship's depth, thereby removing the Main Deck in an identical fashion to the tanker conversion. To compensate for this lack of upper structure, the Midship Section was carefully considered at an early stage to ensure the section modulus was adequate, which led to the adoption of the central longitudinal cofferdam space between cargo holds.

The navigation visibility issues discussed for the oil tanker conversion are equally applicable to the new-build, however as an alternative to providing an aft Wheelhouse of adequate height, we now have the option of a forward location with a fore deck incorporating the bow loading system with ease. With a Wheelhouse located over the Fore Peak, the required height would be minimal and visibility would be maximised. This positioning would also afford some measure of protection to the forward cargo hold deck houses from the encountering of 'green seas'. The apparent inefficient use of the deck area over the stern machinery space(s), would be countered by locating the process modules in this region and hence minimising the side deck areas required, when compared to a tanker conversion.

A detailed investigation of the intact and damage stability characteristics was undertaken for the full range of new-build CGL™ Carrier designs under consideration. The requisite weight of containment system was applied to each design, as well as a process module weight based on whether the ship was to be an 'Integral' or 'Shuttle' carrier. The intact stability results were checked against the IMO requirements and all stability parameters were found to be compliant with the prescribed criteria. Due to the light nature of the CGL™ cargo, the vessel will be required to sail with permanent seawater ballast in most of the double bottom and wing tanks. The damage stability characteristics were calculated and checked against requirements of the IGC Code [1], but again the required 'two compartment' damage as applied along the length of the vessel, and the designs found to be compliant with the prescribed criteria. The allowable longitudinal hull strength, shear stresses and bending moments, were also checked and all cases were found to be acceptable.

The sea-keeping assessments of the new-build CGL™ Carrier designs revealed no particular issues for either the containment system or the ship behaviour. It should be noted that the motions experienced by a forward Wheelhouse and accommodation would be worse than those found on a conventionally sized aft superstructure, however due to the larger size of the new-build designs it was expected that the forward motions would not be extreme and a more significant issue would be the encountering of 'green seas' over the bow.

The 'clean sheet' nature of the new-build designs meant that the ship's propulsion, power generation and integration of the demand from the CGL™ process modules, presented several options to consider. The service speed requirement for all designs has been identified as a minimum of 20 knots, and although the hull form was optimised for a higher speed range (when compared to the oil tanker conversion) it was accepted that a higher powering requirement would exist, especially for the larger cargo capacity designs (4.0 BCF and above).

This large powering demand, and the larger beam on the higher capacity new-build designs, could lend themselves to adoption of a twin screw, twin rudder design, typically twin engine rooms, located port and starboard, immediately aft of the cargo spaces. A single screw/single engine installation for the large CGL™ Carrier designs would provide a very limited choice of engines, or require compromising on the vessel's performance. A twin engine arrangement would vastly increase the choice of engines available, and a twin engine room / propeller arrangement would also increase the redundancy and manoeuvring capability of such a large ship. Furthermore, it allows undertaking of Main Engine maintenance on one unit when loading / unloading, with the other unit available for electrical powering or manoeuvring in a normal 'standby' mode. For manoeuvrability at the loading and offloading buoys, the fitment of Controllable Pitch Propellers and bow thrusters to the new-build designs were also considered, although both are not without cost and technical risk implications.

Given the unlimited nature of the new-build vessel's generating capacity, together with the known load values required for the cargo conditioning system, it makes practical sense to integrate the ship and cargo power systems. The containment system loads during transit are minimal compared to loading and offloading. By the same token the ship load is high only during transit at or near the required service speed, with minimal hotel / service load required during cargo loading and offloading. Comparing the likely ship propulsion load to the cargo loading / offloading system demand, it is clear that only a modest percentage of the ships power need be made available to the cargo system (this percentage varies with the size of the CGL™ Carrier as the process demand stays mostly constant). Hence this allows more options to be considered in satisfying the integration of the ship and cargo power systems.

4. CONCLUSIONS

4.1 TECHNOLOGY BENEFITS & POTENTIAL

Project "in-service" or "first-gas" dates are important when it comes to developing a gas field. The quicker an explorer can develop his field and bring on his gas production the quicker he can start monetizing his gas. Given the modular nature of the process design and if conversion of existing vessels is envisaged the CGL™ Carriers in service date can be greatly reduced. With new ship yards now being made available using new-builds may result in similar expedited project timelines.

Access to remote or 'stranded' gas reserves will be greatly enhanced with the ability of these ships to serve smaller and mid-range fields. This is in the national interest of security of supply for many consuming nations.

The sole requirement for the provision of loading and offloading barges and the associated buoys connecting to conventional undersea gas pipelines, simplifies in-service needs for platform and port facilities. The loading barge that is connected to a buoy allows for the raw production gas to be loaded directly from the wellhead or the flared or associated gas from an FPSO where on it is processed and conditioned. The offloading barge and associated buoy especially offer advantages in an era of difficulties in locating receiving terminals. The NIMBY (Not-In-My-Back-Yard) and NIMTO (political: Not-In-My-Term-Of-Office) syndromes afflicting many proposals world wide is likely to lessen with the facilities being placed safely offshore, out of site of land in many parts of the world.

The ability to 'dial-in' the required gas properties for the offloaded product means that the gas inter-changeability concerns effecting many markets viewing new supplies of LNG becomes a non issue. In many markets, particularly the low BTU specification requirements for the US market, many constituent mixes of imported gas are restricted as they require some form of blending, or processing at a cost, to suit trouble free safe burning on existing equipment. In Korea and Japan high BTU specification gas is the norm, and some pick-up of high BTU hydrocarbons for blending is possible on the outward voyage of the Integral gas carrier consigned to load a relatively low BTU shipment of natural gas. If a shuttle carrier configuration is employed that uses the services of an Offloading Barge at market, the ability to 'dial-in' the required gas properties for the offloaded product is maintained.

The route of such deliveries need not be fixed given the flexibility of gas loading and offloading installations. The commercial possibility of a World spot market for natural gas will without doubt emerge once these gas carriers enter service.

The improved transportation tariff offered by more effective technology, results in higher 'netbacks' to producers, which in turn translates to better royalties for producing countries or local governments. This is the bottom line to the success of this venture, and others with the same objectives.

4.2 CGL™ CARRIER ISSUES

The stability and longitudinal strength aspects of a ship (tanker) conversion to a CGL™ Carrier do not appear to present any significant problems, although differing donor vessel types will have differing 'issues' due to the variance in their structural configuration. From our studies, the key to the conversion of an existing single hull oil tanker to a CGL™ Carrier is in getting adequate cargo hold floor area for the required containment pipe capacity without stacking the pipes to an excessive centre of gravity height. Further aspects of a vessel conversion have been studied in detail, including intact stability, damaged stability, longitudinal strength, sea-keeping, and changes to the vessel's equipment and piping. No significant issues have been identified with the above studies.

The conversion route to the shuttle or integral CGL™ Carrier has proved to be both feasible and practical, given the current international new-building shipyard work load and the need for 'speed to market'. The benefit of the new-build CGL™ option over the tanker conversion, is the ability to optimise the cargo hold region for the desired capacity by selecting the most favourable vessel particulars which also suit the main propulsion system selected, and the deck area for the process modules.

The overall design feasibility of very large CGL™ Carriers does not appear to present many major issues at this stage in their development. The main area of 'technical' risk is the large size of the higher capacity CGL™ Carriers (4.0 BCF and above), which will be amongst the larger sized commercial vessels afloat, and may present issues with regard to scantlings and draft / beam restrictions during build and operation. Although this may be considered significant, this type of issue is to be expected when developing a new vessel type, and should not be considered detrimental. Indeed the 'buoy to buoy' configuration of a CGL™ gas train means that issues of draft and manoeuvring are lower down the design priority list. Rather it is the identification of these issues so that mitigating steps (such as further studies, testing, alternative options) can be investigated to provide a fully feasible vessel design at the earliest opportunity.

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6. REFERENCES

1. 'International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk' (IGC Code), International Maritime Organisation, 1993 Edition
2. The International Convention for the Prevention of Pollution from Ships - 1973 (MARPOL), International Maritime Organisation, 2006 Consolidated Edition
3. International Convention Of The Safety Of Life At Sea – 1974 (SOLAS), International Maritime Organisation, 2004 Consolidated Edition

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